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THERMAL REGULATION DURING EARLY ACCLIMATIZATION TO WORK IN A HOT DRY ENVIRONMENT

*Sub-project under High Temperatures, Study of Physiological Effects of. (MDFRL 2-17-1) approved September 1942.

U.S. Army. Medical Dept. Field Research Laboratory,
Fort Knox, Ky.

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ABSTRACT

THERMAL REGULATION DURING EARLY ACCLIMATIZATION TO WORK IN A HOT DRY ENVIRONMENT

OBJECT

To determine the changes in thermal regulation of early acclimatization to a hot, dry environment.

RESULTS AND CONCLUSIONS

Calorimetric measurements and clinical observations during early acclimatization were made on three men working at a metabolic rate of 180 Cals/m^2/hr in a very hot, dry environment.

On beginning work in these surroundings, heat was gained at a high rate by metabolism, convection and radiation. Deep and peripheral tissue temperatures rose rapidly. The climb in skin temperature reduced the environmental stress, since it diminished the thermal gradient for convection and radiation. At the same time, however, the internal gradient for the outflow of heat from the deep tissues was narrowed and the deep temperature rose excessively despite a greatly elevated peripheral blood flow. The heavy load on the circulation probably accounted for many of the symptoms of the unacclimatized state.

The principal thermal adjustment of acclimatization was the development of a higher rate of sweat secretion. The added cooling by evaporation lowered the skin temperature and improved the internal thermal gradient. Heat outflow from the deep tissues was increased and a reduction in peripheral flow was possible. Signs of circulatory stress diminished greatly. The heat content of the body after acclimatization remained high, but the heat was absorbed in the peripheral tissues and the critical deep tissue temperature was maintained at a nearly normal value.

RECOMMENDATIONS

None.

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THERMAL REGULATION DURING EARLY ACCLIMATIZATION TO WORK IN A HOT DRY ENVIRONMENT

I. INTRODUCTION

A. Acclimatization

When man works for the first time in a very hot environment his body temperature rises to an abnormally high level. This is associated with psychomotor, gastro-intestinal, and circulatory disturbances which often prevent effective work and may lead to heat exhaustion. On repeating the work in the same hot environment on successive days, he becomes acclimatized (1,2,3,4,5); that is, he develops protective mechanisms which allow him to control his temperature at a level compatible with satisfactory physiological function, and to work nearly as easily in the heat as in the cool.

B. Rectal and Skin Temperature during Work

The experiments of Nielsen (6) demonstrate that if work is carried out at a constant metabolic rate, the rectal temperature during a period of 40-50 minutes rises to a plateau value, the height of which is proportional to the metabolic rate and independent of the environmental conditions unless these are extreme. It appears, therefore, that the elevated rectal temperature of work is under physiological control and is not the result of inability to dissipate the increased metabolic heat because, if this were the case, the temperature would be lower in cool environments where heat loss can be accomplished much more easily. Nielsen noted that this control cannot be maintained in very hot environments and abnormally high temperatures are reached. The skin temperature, on the other hand, is always influenced by the thermal nature of the surroundings and is normally higher in hot environments (6,7).

C. Heat Content and Thermal Flows

Changes in the rectal temperature can be used as rough indices of changes in the average temperature of the deep tissues of the body (8), and variations in the mean skin temperature indicate in similar fashion the variations in temperature or heat content of the peripheral tissues. Burton and Hardy and DuBois (8,9) have developed empirical formulas in which measurements of the rectal and mean skin temperatures are combined to indicate the change in the average temperature or heat content of the body as a whole. A change in heat content can also be determined by the method of partitional calorimetry, developed by Winslow, Herrington, and Gagge (10,11). The rates of production and transfer of heat from man to his environment are measured separately in each channel of flow, and are added algebraically to give the net rate of gain or loss of heat by the body. When the net rate is multiplied by time the change in heat content is obtained:

$$\Delta H_{body} = (\text{net rate})(\text{time}) = M + E + C + R \ (\text{time})$$

where M = the rate of metabolic heat production
E = the rate of evaporative heat loss
C = the rate of heat transfer by convection to the surrounding air
R = the rate of heat exchange with the environment by radiation

By combining these calorimetric procedures it is possible to obtain a rough measure of thermal flow from the deep tissues to the surface by direct tissue conduction and by transport in the blood stream (12). From the last, the volume of the "peripheral" blood flow can be estimated.

These relationships were investigated in men working in the heat to determine if possible the mechanisms preventing the excessive rise in body temperature as acclimatization developed.

II. EXPERIMENTAL

A. Apparatus and Methods

1. General Design of the Experiment

The temperatures and thermal flows of 3 subjects were determined during 1 hour of work on 10 successive days in the heat, a period long enough for the early changes of acclimatization to occur (2,4). The test hour of work was divided into five 12 minute intervals in each of which measurements were made.

2. The Environment

A hot, dry (desert) type of environment was chosen for study in which the air and radiation temperatures of the walls were 120°F., the wet bulb temperature 80°F., and the wind velocity 450 feet per minute. These conditions imposed a large convective and radiative heat load on the subject, and the evaporation of sweat was rapid.

3. Subjects and Schedules

The physical characteristics of the soldiers who served as subjects appear in Table 1. These men were brought into good physical condition by long daily marches during a preliminary period of 23 days.

TABLE 1

PHYSICAL CHARACTERISTICS OF SUBJECTS

Subject	Age yrs.	Height cms.	Weight Kg.	S. A. M^2
A	18	178	68.5	1.87
B	20	171	61.9	1.73
C	25	179	72.9	1.91
Average	21	176	67.8	1.84

In the last 9 days of this time they practiced treadmill walking and other phases of the routine followed subsequently in the heat. During the final 5 days, measurements were made under the same conditions of work as in the heat, but in a cool, windy environment with air and radiant temperatures of 78°F. and a wet bulb temperature of 60°F.

On each of the 10 "hot days" which followed, the men were exposed to high environmental temperatures for a total of 7 hours. Measurements were always made in the first, or test hour, and the men then rested until the last 2 hours when they again worked at a metabolic rate of approximately 130 $Cals/m^2/hr$. When not in the test environment, the subjects lived in a laboratory room conditioned to 78°F.

Further control data were collected in the original cool environment in the 2 days which followed the period of heat exposure.

All determinations were made with the subject in the nude except for shoes and socks.

Base line measurements of skin temperature, rectal temperature, and pulse rate were made in a cool, still air environment of 78°F. just before the start of every test hour.

4. The Test Hour

Calorimetric determinations were made in a wind tunnel placed in the center of a laboratory room. The floor of the tunnel consisted of a treadmill on which the subject walked, facing the air stream, at 2.5 miles per hour up a 2.5% grade. In each test hour, there were five 10 minute periods of marching separated by 2 minute intervals in which the man stepped off the mill and seated himself on a balance in a wind shielded booth. The wind velocity and the temperatures of the air, tunnel walls, and skin were measured during each marching period. The metabolic rate was measured throughout the 1st, 2nd, and 5th periods. The weight and rectal temperature were determined in each 2 minute interval in the booth.

The pulse rate was counted during each working period, and blood pressure measurements on a tilt table were made at the finish of the hour. Water at body temperature and salted to 0.1% was drunk during each interval in the weighing booth in an amount approximately equal to the quantity lost by sweating.

5. Methods of Measurement

a. Environment

Dry and wet bulb temperatures of the air were measured by mercury thermometers in motor driven psychrometers. Air movement was determined by a hot wire anemometer and an Alnor velometer. The radiant temperature was obtained by averaging the readings of a radiometer pointed at the 6 presenting wall surfaces.

b. Body Temperature

Rectal temperature was measured by clinical rectal thermometers. The temperature of the skin was determined radiometrically at 6 points and each reading was weighted according to the area of skin represented (Hardy and DuBois 13,14,15) and summed to give the mean skin temperature (Table 2).

TABLE 2

WEIGHTING FACTORS FOR THE DETERMINATION OF THE MEAN SKIN TEMPERATURE

Area	Cheek	Forearm	Palm	Thigh	Back	Chest	Total
Weighting %	14	11	5	32	17	18	100

c. Oxygen Consumption

Expired air was collected in a Tissot gasometer and duplicate samples were analyzed for CO_2 and O_2.

d. Weight Change

A beam balance sensitive to 4 g. was used.

e. Pulse Rate

This was determined by palpation.

B. Calculations

1. Calculation of the changes in body heat content

a. The change in heat heat content of the body was calculated from the specific heat and the changes in the rectal and mean skin temperatures (8,9).

$$\Delta H_{total} \text{ in Cals.} = (0.67\ \Delta T_r{}^{\circ}C. + 0.33\ \Delta T_s{}^{\circ}C.)(\text{Wt. in Kg.})(0.83)$$

b. This was roughly partitioned into changes in the heat content of the deep and peripheral tissues:

$$\Delta H_{deep} \text{ in Cals.} = (0.67\ \Delta T_r)(\text{Wt. in Kg.})\ (0.83)$$

$$\Delta H_{peripheral} \text{ in Cals.} = (0.33\ \Delta T_s)\ (\text{Wt. in Kg.})\ (0.83)$$

2. Calculation of Heat Flow

a. Metabolism (M) was calculated from the oxygen consumption using the caloric equivalent of oxygen at the measured R.Q., and correcting for external work.

b. Evaporation (E) was calculated from the water loss by the skin and lungs in a given time, and the latent heat of vaporization of water (0.576 Cal/g). Water loss was measured by weight change, corrected for water ingestion and the excess of CO_2 excreted over O_2 consumed:

$$E \text{ in Cals/hr} = \frac{(0.576\ \text{Cals/g})(\text{Wt.}_{corr.})}{(t \text{ in hr.})}$$

c. Convection and radiation were calculated as the sum of both factors, (C + R):

Because wind velocity in this experiment was constant, convection varied only with the difference between the air and mean skin temperature:

$$C = K_c(T_a - T_s)$$

The radiating surface area and emissivities of the man and his surroundings were assumed to be constant, therefore radiation varied only with the difference between the 4th powers of the absolute values of wall and mean skin temperature (14):

$$R = K_r\ (T_w^4 - T_s^4)$$

When the 1st power difference was substituted for the 4th power difference in this last relationship only a small error was introduced, since measurements were confined to a narrow range of temperatures. As air and wall temperatures were always the same, C and R were considered functions of the same temperature difference.

Convection and radiation were first calculated for all experimental periods in which there was no change in rectal and skin temperatures. Under these circumstances, there was no change in heat content, and the algebraic sum of all heat flows equalled zero:

$$M + E + C + R = 0$$

This equation could be solved for C + R, since M and E had been already determined. A large number of coefficients for C + R transfer per degree of temperature difference between the air and skin was then calculated:

$$K_{C + R} \text{ in Cals/hr/}^{\circ}\text{C} = \frac{C + R \text{ in Cals/hr}}{T_a - T_s}$$

The average of these values was 18 Cals/hr/°C.

Using this coefficient, C + R was then calculated for all periods according to the difference between the air and mean skin temperature, regardless of any change in heat content:

$$C + R \text{ in Cals/hr} = (18)(T_a - T_s)$$

d. In certain cases C + R was partitioned roughly by making an independent calculation of R, using the method described by Hardy and DuBois (14).

e. The thermal flows were summed and the overall, or net rate of gain or loss of heat to the body was determined. Heat gains were considered positive and heat losses negative. The net rate was multiplied by the time and a second value for the change in body heat content was obtained:

$$\Delta H \text{ in Cals/hr} = (M + E + C + R)\ (t)$$

3. Calculation of the "peripheral" blood flow

Peripheral blood flow was calculated by the method of Hardy and Soderstrom (12), using the equation:

$$P\,F = \frac{M - \frac{\Delta H}{t}}{T_r - T_s} - K_{cd}$$

where P F = "peripheral" blood flow in liters/m^2/hr (equivalent to Cals/m^2/hr/°C)

and K_{cd} = conductivity of peripheral tissue in Cals/m^2/hr/°C

4. General

All calculations were made for each subject individually but, as the trend of results was similar for all men after corrections for differences in surface area, the results were combined into average values.

C. Results

1. Clinical Observations

During the 10 days in the hot environment, the characteristic sequence of reactions of early acclimatization appeared in all 5 subjects (1,2,3,4,5). On the 1st day the men completed the test hour with great difficulty, and all complained of great fatigue, dizziness, and a sense of oppressive heat. There was marked flushing of the face, the gait became unsteady, and 2 of the men developed orthostatic hypotension with syncope shortly after stopping work. On the 2nd day, these symptoms and signs were less marked and by the 4th and 5th days had nearly disappeared. On the 10th day the men worked easily, and there was nothing in their appearance to suggest any strain not incurred by the same work in the cool.

The pulse rate climbed progressively on the 1st day to reach an average value at the end of the hour of 160 beats per minute (Fig.1, top panel). In the ensuing 4 days, the rate dropped markedly, showing a definite tendency to reach plateau values. On the 10th day, the pulse rate rose only to 125, but this was 15 beats per minute higher than the rate in the cool, and evidenced that some additional stress on the circulatory system still remained.

2. Rectal and Mean Skin Temperatures

The rectal temperature in the cool environment rose rapidly at first but levelled off in the last periods of each hour of work (Fig. 1, 2nd panel). The final temperatures reached were nearly the same from day to day and established roughly the normal plateau value of deep temperature of 37.8°C. for the grade of work being carried out.

The rectal temperature on the 1st day in the heat, on the other hand, rose rapidly and continuously to 39°C. (102.2°F.), exceeding the normal value by 1.2°C., and it probably would have climbed higher had the work

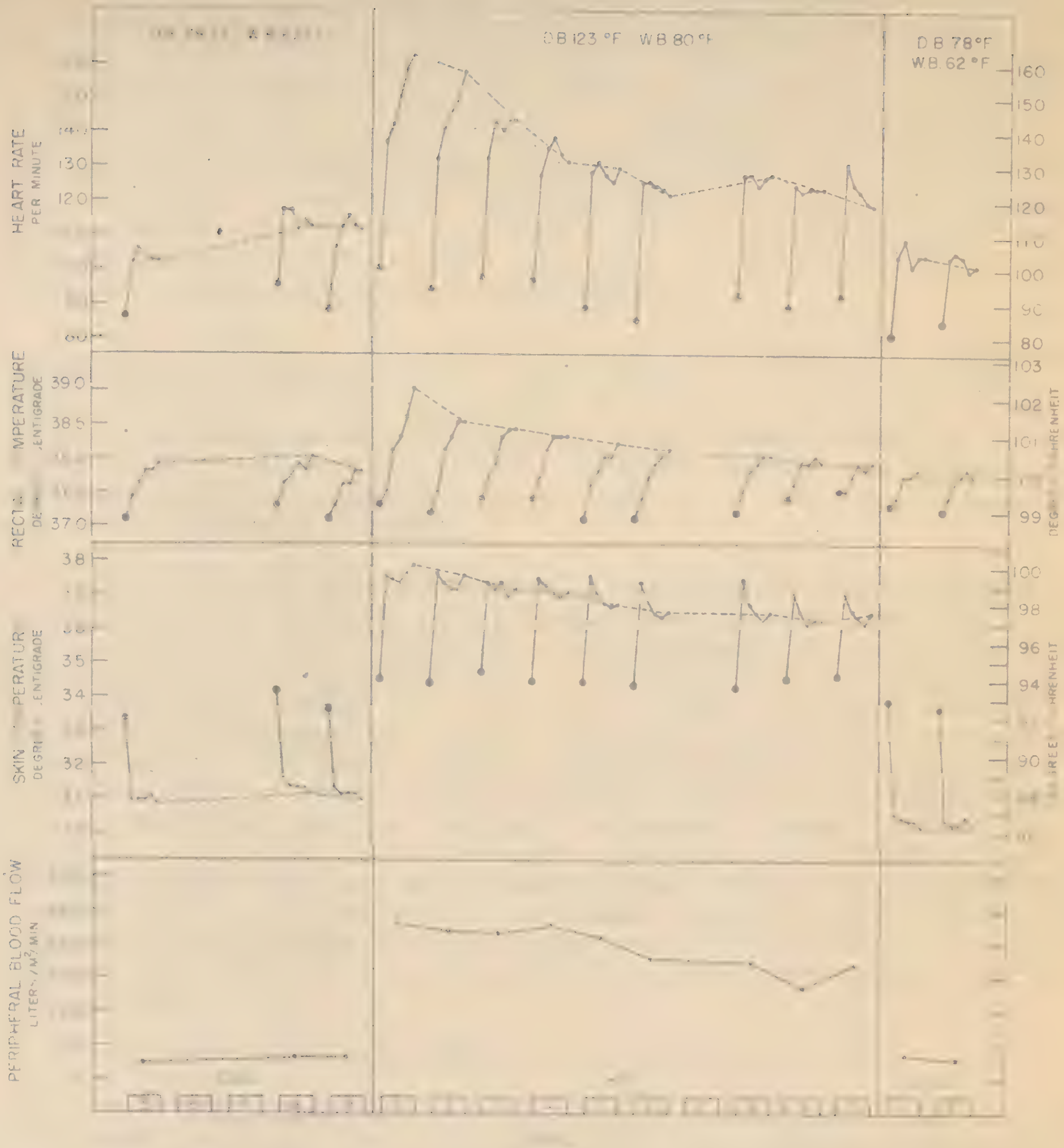

Fig. 1. The Heart Rate, Rectal and Mean Skin Temperature and Peripheral Blood Flow during Work in the Cool and during Acclimatization to the Same Work in Severe Heat.

In the upper three panels the solid lines connect the base line determinations taken at rest in a cool environment (large points) with the five readings (small points) taken in the course of the test hour on each day. The broken lines connect the final readings from day to day. In the 4th panel, the values are averages for the entire hour.

periods been extended. On the 2nd day, this rise was considerably less and became progressively lower on each of the following days, until, on the 10th day, the final reading obtained was 38°C. (100.4°F.). This was only 0.2°C. above the average value established in the cool. In the last days in the hot environment, a tendency for the temperature to level off at a plateau value was quite distinct and the readings on the 9th and 10th days were very nearly the same, suggesting that any further fall in temperature would be slight. It was clear, therefore, that as acclimatization progressed the excessive rise in deep temperature had been largely prevented and, after 10 days in the heat, thermal regulation had improved sufficiently to control this temperature to near normal levels.

The skin temperature in the cool environment fell sharply below the base line readings as the subject began work in the wind tunnel (Fig. 1, 3rd panel). After the initial drop, the values remained fairly stable in the remainder of each test hour at an average figure for all cool days of 30.5°C. This was roughly 7°C. below the average deep temperature, and established a large gradient for the outflow of heat from the deep tissues to the surface of the body.

The mean skin temperature in the first few minutes of work on the 1st day in the heat rose precipitously above the base line level to the very high value of 37.5°C. (99.5°F.), and subsequently in the course of the hour it climbed slightly higher (Fig. 1, 3rd panel). In the following days, the initial spike remained high but by the 3rd day, a definite tendency appeared for the temperature to fall thereafter, and this fall was pronounced by the 10th day. The overall drop in the final skin temperature during the 10 days was slightly greater than the parallel fall in final rectal temperature (broken lines) and thus improved the internal thermal gradient for heat flow to the skin. In the 1st hour in the heat, for example, the average difference between deep and skin temperature was only 0.8°C., a difference so small that heat did not move in sufficient quantity to the surface of the body, and the deep temperature rose excessively. By the last day, this gradient was 1.3°C., still a very small value, but nevertheless a significant increase.

3. Peripheral Blood Flow

The peripheral blood flow (Fig. 1, bottom panel) was very nearly the same in all cool days. On the 1st hot day, a sevenfold increase to a very high value occurred. The flow diminished markedly as acclimatization progressed, but remained far above the level in the cool.

4. Changes in Heat Content

In the cool environment there was an average loss in body heat content of 22 Cals/m^2. This was due to a large drop in the peripheral temperature which outweighed the rise in deep temperature. In all days in the heat, on the other hand, there was a big gain in heat content since both the rectal and skin temperatures rose above the base line readings. On the 1st day this was 71 Cals/m^2 but, in the following days, the gain became progressively smaller until by the 10th day it was only 35 Cals/m^2, an amount still 57 Cals/m^2 above the final values reached in the cool.

When the changes in heat content for the hot and cool days were partitioned between the deep and peripheral tissues an interesting relationship appeared. Deep heat content in the cool environment rose on the average 10 Cals/m^2. In the hot environment on the 1st day the deep heat content rose 35 Cals/m^2, but by the 10th day it rose only 12 Cals/m^2 or 2 Cals/m^2 above the level in the cool. The total difference of 57 Cals/m^2 between the final total heat content in the heat and in the cool was almost entirely (97%) explained by a change in heat content of the peripheral tissues only.

These changes in temperature, blood flow, and heat content, which had been accompanied by parallel and marked improvement in clinical symptoms and signs, were due to physiological adjustments which accelerated the rates of heat transfer from the man to his environment.

5. Thermal Balance

The rates of gain and loss of heat in the cool and hot environments have been charted day by day in Figure 24. In the cool, metabolism was the only channel of heat gain; evaporation, radiation and convection were routes of heat loss. The net thermal flow, or algebraic summation of all rates, can be visualized by the difference in the height of the columns of each pair. In the cool days, generally, the rate of loss exceeded by a small margin the rate of heat gain, leading to a slight fall in heat content.

The effect of the hot environment was striking. Here, heat was gained by metabolism at a rate nearly the same as in the cool and, in addition, by convection and radiation which had now become very large channels of thermal inflow. The only remaining means for cooling was evaporation and although this rate increased thirteenfold, it was not sufficient to balance the rate of gain; there remained, therefore, a large net flow into the body leading to the excessive rises in body heat content in the first days of exposure.

The changes in thermal flows during the hot days are shown more clearly in Figure 25. The rate of heat gain by metabolism (1st panel) diminished uniformly but the overall fall was slight (8 Cals/m^2/hr). It was not clear from these data whether this change was a part of the acclimatizing process, as was maintained in studies by Robinson et al. (9), or a training effect due to practice in treadmill walking. On the other hand the rate of heat gain by convection and radiation increased (2nd panel). The total rise of 19 Cals/m^2 was explained by the fall in skin temperature previously noted. While this change widened and improved the internal thermal gradient for the outflow of heat from the deep tissues, at the same time it widened the thermal gradient between the body surface and the environment. Since convection and radiation were functions of the skin to environmental temperature difference, the flow of heat into the body by these channels was increased. The net effect of alterations in metabolism, convection and radiation led to an overall rise in the rate of heat gain to the body of 11 Cals/m^2/hr.

The rate of body cooling, however, rose to a greater extent. The total gain in evaporation was 40 Cals/m^2/hr, (3rd panel), with the most rapid changes taking place in the first 4 days, the period of time that was apparently of the most importance in the acclimatizing process. The in-

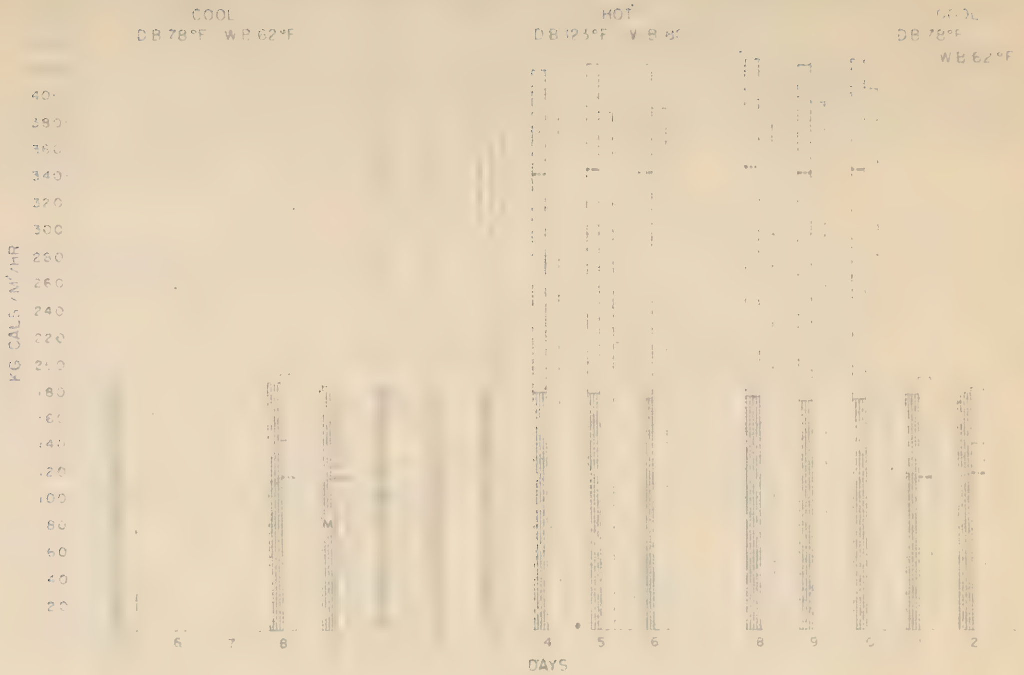

FIG. 2 A

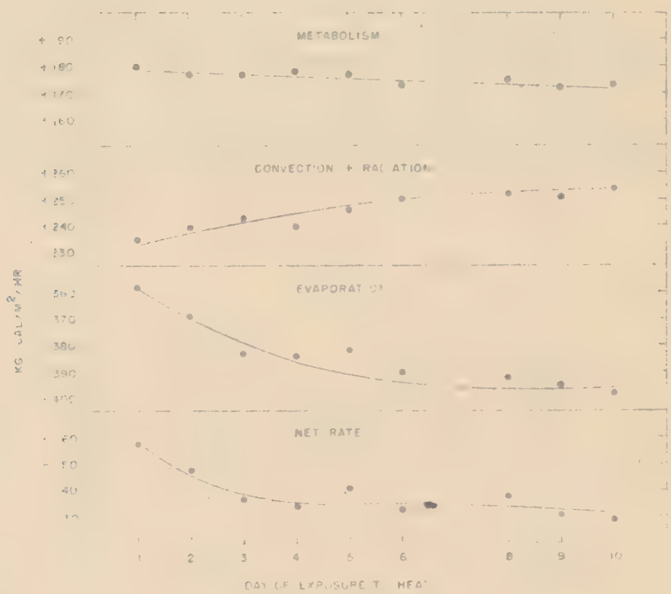

FIG. 2B

Fig. 2A. Thermal Flows during Work in the Cool and Hot Environments.

The left column of each pair show the channels and magnitude of thermal inflows to the body, and the right column the thermal outflows. Key: M - Metabolism; C - Convection; R - Radiation; E - Evaporation

Fig. 2B. The Changes in Thermal Flows during Acclimatization.

creased cooling could only be explained by a higher rate of sweat secretion.

The sum of all changes in heat flows was a considerable decrease in the net rate of heat gain to the body (bottom panel). Thus the lowered temperatures and heat content observed during the progress of acclimatization could be explained.

It could be demonstrated that thermal balance was restored by determination of the rates of heat exchange by periods within each test hour. In Figure 3, these rates are plotted for the hour of work on the 1st day (solid line), and the 10th day (broken line) for 12 minute intervals. Metabolism was constant on the 1st day but fell slightly on the 10th day (1st panel). Convection plus radiation, on the other hand, rose to an appreciably higher rate on the 10th day (2nd panel). The greatest difference occurred in evaporation (3rd panel). Values on both days were similar in the first 12 minute interval, but, in the 2nd period on the 10th day, evaporation rose and remained a larger value during the rest of the hour. These changes resulted in the net flows of heat shown in the bottom panel. It can be seen on the 1st day, that the initial high rate of gain was considerably reduced between 12 and 24 minutes, but the lowest value reached at any time was 27 Cals/m^2/hr; in other words, heat flowed into the body throughout the hour, and body temperature and heat content were always rising. The situation was quite different on the 10th day. Heat flowed into the body at a high rate in the first 12 minutes, but thereafter the rate fell for practical purposes to zero. Thus, thermal imbalance existed only in the first part of the hour, and it was in this time interval that the major rises in rectal and skin temperature occurred. In the remainder of the hour the men were in thermal equilibrium: the rates of inflow and outflow were approximately equal, and heat content and body temperatures were stabilized.

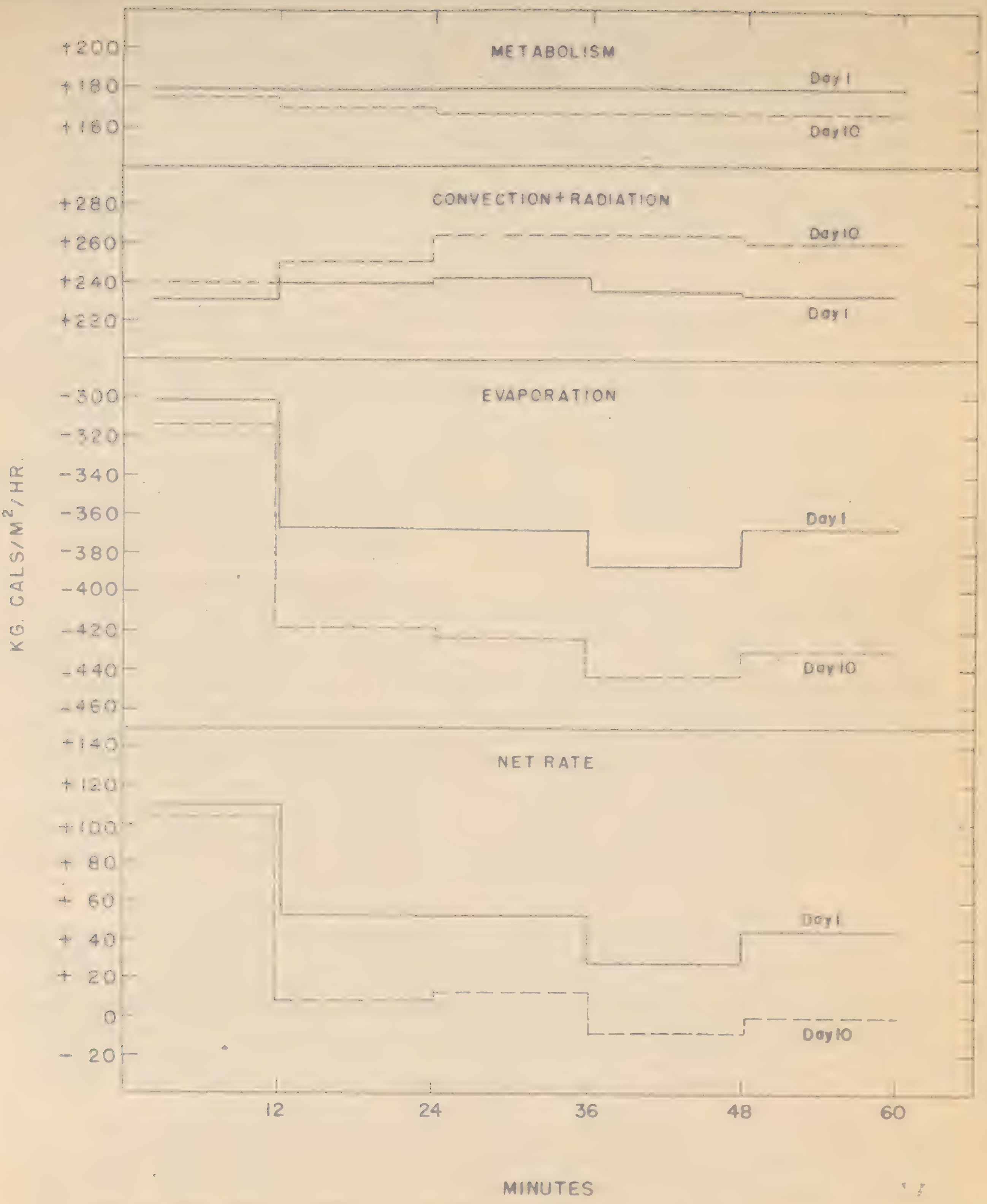

Fig. 3. The Restoration of Thermal Balance during Acclimatization.

The rates of gain and loss of heat to the body are shown by 12 minute intervals during the test hour on the 1st and 10th day of work in the heat.

III. DISCUSSION

The temperature of the deep tissues, or some part of these tissues, is apparently critical to normal physiological function; otherwise, it would be difficult to explain the observations of Nielsen (6) and the evidence of this study that the rectal temperature is regulated to the same value in men working at a given rate in widely different types of environment. When the environment is so hot that physiological controls are inadequate to maintain this temperature, severe clinical symptoms and signs are manifested, as noted in the first test days of this study.

The principal thermal adaptation of acclimatization was the ability to secrete sweat at a more rapid rate. The total increase in evaporation by the 10th day was 40 $Cals/m^2$. The net cooling effect was less, however, since the skin temperature was lowered and heat gain by C + R was greater by 19 $Cals/m^2$. The lower skin temperature permitted a greater outflow of heat from the deep tissues, and the net cooling advantage of 21 $Cals/m^2$ was adequate to ensure a nearly normal deep temperature. The heat content of the acclimatized man was still 57 $Cals/m^2$ higher than when working in the cool, but only 3% of this was in the deep tissues and 97% was in the peripheral tissues, the absolute temperature of which is not apparently critical to normal physiological function.

The ability of the peripheral tissues to take up large quantities of heat without leading to significant changes in the deep temperature is an important mechanism in thermal regulation. First, it permits the body to endure large imbalances in the rates of gain and loss of heat over considerable periods of time, and obviates the necessity for precise adjustments in the control of thermal flows. Rapid fluctuations in environmental and working conditions can be encountered without immediate changes in peripheral blood flow, sweating, or heat production. Second, the absorption of heat causes the temperature of the skin to approach the environmental temperature and diminishes heat exchange by convection and radiation. The skin temperature in the heat, for example, rose 3°C. above the base line value reducing the heat load on the man through C + R by 54 $Cals/m^2/hr$.

Different levels of peripheral temperature in relationship to the deep temperature are possible because of changes in the peripheral blood flow. Thus, on the 10th day, when the peripheral temperature was high and the internal gradient small, a sufficient outflow of heat to the surface occurred because of the large peripheral flow. A sufficient rise in flow to compensate for narrowing of the gradient can occur within certain limits only. In the unacclimatized state, the gradient was too small and, despite a very high flow, the normal deep temperature was exceeded.

The requirement for a greatly elevated peripheral flow combined with the demand for blood to the active muscles placed a heavy load on the circulation. This seems the most probable explanation for the severe symptoms of circulatory insufficiency on first exposure to the heat.

IV. CONCLUSIONS

On beginning work in the test environment, heat was gained at a high rate by metabolism, convection and radiation. Deep and peripheral tissue temperatures rose rapidly. The climb in skin temperature reduced the environmental stress, since it diminished the thermal gradient for convection and radiation. At the same time, however, the internal gradient for the outflow of heat from the deep tissues was narrowed and the deep temperature rose excessively despite a greatly elevated peripheral blood flow. The heavy load on the circulation probably accounted for many of the symptoms of the unacclimatized state.

The principal thermal adjustment of acclimatization was the development of a higher rate of sweat secretion. The added cooling by evaporation lowered the skin temperature and improved the internal thermal gradient. Heat outflow from the deep tissues was increased and a reduction in peripheral flow was possible. Signs of circulatory stress diminished greatly. The heat content of the body after acclimatization remained high, but the heat was absorbed in the peripheral tissues and the critical deep tissue temperature was maintained at a nearly normal value.

V. RECOMMENDATIONS

None.

VI. BIBLIOGRAPHY

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None.

VI. BIBLIOGRAPHY

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